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Benefits and constraints for use of FGD products on agricultural land

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Abstract

Considerable amounts of coal combustion products (CCPs) are generated when coal is burned for generation of electricity. To meet Clean Air standards, large amounts of S must not be emitted into the atmosphere, which means considerable amounts of flue gas desulfurization products (FGDs) are and will be produced. Beneficial uses of FGDs are continually being sought to reduce waste, decrease cost of disposal, and provide value-added products. Beneficial agricultural uses of FGDs include application as amendment to acidic soil to mitigate low pH problems (Al and Mn toxicities); provide plant nutrients (i.e. Ca, S, and Mg); improve soil physical properties (e.g. water infiltration and soil aggregation); help alleviate soil compaction and improve aggregate stability of sodic soils; and inactivate P under high P-soil conditions to reduce P runoff. Co-utilization of FGDs with organic materials (manures, composts, biosolids) should also provide many benefits when used on land. Constraints for use of FGDs on agricultural land could be both insufficient or excessive amounts of $CaCO_3$, CaO, and/or $Ca(OH)_2$ in raising soil pH insufficiently or too much; excessive Ca to cause imbalanced Mg, P, and K in soils/plants; Ca displacement of Al from soil exchange sites to induce Al toxicity in plants; high B to induce B toxicity in plants; excessive sulfite which is toxic to plants; and excessive amounts of undesirable trace elements (e.g. As, Cd, Cr, Ni, Pb, and Se) which could potentially contaminate water and pose toxicity to plants/animals/microorganisms. Most constraints should not impose problems for FGD use on land. Published by Elsevier Science Ltd.

Keywords: Al, B, and sulfite toxicities; Nutrient deficiencies; P availability; Soil amendment; Soil pH; Soil physical properties; Trace element contamination

1. Introduction

Over half (56%) of the electricity produced in USA arises from burning coal [55], which results in considerable amounts of coal combustion products (CCPs) being produced (98 million (m) metric tons in 1998) [6]. Many of these CCPs could be used beneficially; but presently only about 29% of CCPs are utilized in USA [6]. Most CCPs in USA are presently discarded, especially in landfills, and landfill sites are becoming more limited and disposal costs continue to increase. The value of many CCPs has been well established by research and commercial practice in USA and elsewhere, so beneficial use of CCPs should be sought. Otherwise, large amounts of the CCPs will be stored as landfill plots and/or mountains of solid waste leaving environmental problems and undesirable legacies for future generations. The American Coal Ash Association (ACAA) reported for 1998 that 34% of fly ashes, 31% of bottom ashes, 80% of boiler slags, and 10% of flue gas desulfurization products (FGDs) were being used beneficially [6]. Beneficial uses of FGDs could be on agricultural/pasture/forest land. Even though agricultural use of FGDs may not be high compared to cement, construction/road/structural fill, and many other uses, application on agricultural lands could be important in management of FGDs. Information on beneficial use of FGDs is limited, since FGDs are the newer Clean Coal Technology products.

The objective of this article is to provide information about some of the benefits and constraints of FGD use on agricultural land.

2. Benefits

Resource rather than waste: As long as FGDs (and other CCPs) are considered wastes, they are controlled by environmental laws that usually require disposal rather than reuse. Many of these materials present relatively little risk to the environment, yet must be disposed of as solid waste. When many natural resources are disposed, additional problems or undesired conditions may be created. This concept needs changing so that beneficial use is more prevalent. Attempts have been made to remove some regulatory barriers to beneficial use of FGDs (and other CCPs), but progress has been slow [40]. A beneficial use of FGDs

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Table 1
pH (1 soil:1 10 mM $CaCl_2$) of acidic soil amended with different levels of various FGDs and other CCPs (from Clark et al. [16])

CCP in soil (%)	Fly ash		FBC[a]		Stabilized FGD		FGD gypsum		
	Class F	Class C	FBC-1	FBC-2	FGD-1	FGD-2	FGD in soil (%)	FGD-A	FGD-B
0	3.91	4.03	4.00	4.03	3.91	4.00	0	4.00	4.00
0.5		4.64	4.88	4.72		4.23	5	4.07	4.29
1	4.02	5.06	5.70	5.26	3.97	4.29	10	4.18	4.36
2	4.04	5.43	7.09	6.08	4.17	4.58	25	4.26	4.78
3	4.13	5.88	7.61	6.54	4.38	4.78	50	4.65	5.77
5	4.44	6.33	8.19	6.74	4.97	5.38	75	5.52	6.54
10	4.82	7.52		7.19	5.93				
20				8.25					
25		7.60							
CCE[a] (%)	6	45	75	89	39	39		< 1	5
FGD/CCP pH	11.60	11.60	11.50	11.80	9.6	10.6		8.6	8.9

[a] FBC, fluidized bed combustion product; CCE, calcium carbonate equivalency.

could be application on land to provide benefits to soils/plants. Soils have large buffering and diluting effects on these kind of materials. This could be important in management of FGD materials. Existing information is limited and new knowledge needs to be generated to eliminate hazards, promote safe use, and provide identified benefits.

Mitigate soil acidity: One foremost beneficial use of FGDs on land could be as an amendment to mitigate low soil pH problems (Table 1). Many acidic soils have sufficiently low pH ($< \sim 5$) to be detrimental to plants [23,54]. Some deleterious effects of soil acidity are greater solubility of Al and Mn which are toxic to root growth [23], lower solubility of P, Ca, Mg, Zn, and Cu which are essential to plants [36], and greater solubility of many trace elements (Cd, Cr, Pb, and Ni) which may be phytotoxic to plants and detrimental to animals/humans/microorganisms when sufficient quantities of trace elements accumulate in plant tissue consumed by organisms [27]. The pH of acidic soils usually needs to be increased to alleviate many detrimental effects these soils induce on plants. Although limestone ($CaCO_3$ and/or $CaMg(CO_3)_2$) has been commonly used as an amendment to increase soil pH, many FGDs, especially those containing alkalizing agents (e.g. CaO, $Ca(OH)_2$, and $CaCO_3$), have good potential to increase soil pH. One major problem with calcitic limestone is that the major reactive compound ($CaCO_3$) is so insoluble that it is only effective at the site of incorporation in soil and not readily leached. Thus, soils must be cultivated/disturbed to distribute limestone within profiles or to make it available in deeper profiles. Tilling soil is common for the production of cultivated crops, but not for pasture, perennial, and shrub/tree plants. The major active constituent in FGDs after oxidation is $CaSO_4$ ($CaSO_4$ is used here to mean $CaSO4{\cdot}2H_20$ (gypsum) and other $CaSO_4$ products like $CaSO_4{\cdot}1/2H_20$), which is considerably more soluble than $CaCO_3$ [31], and has potential to leach into lower soil profiles. Enhanced concentrations of Ca and S leached into subsoil may provide roots needed mineral nutrients, reduce availability of toxic elements (Al, Mn, Cd, Cr, and Pb), increase solubility of some essential mineral nutrients (P, Zn, Cu, and Mo), and promote root growth. Many of these benefits could be realized without disturbing surface soil.

Table 2
Change in water infiltration and soil loss from different types of soil treated with FBCs at 5% slope and 64 mm added water h^{-1} (modified from Norton and Dontsova [37])

Soil class	pH	Water infiltration (%)		Soil loss (%)	
		−FBC	+ FBC	−FBC	+ FBC
Loam	6.5	100 (6.2)[a]	287	100 (0.113)[b]	58
Silt loam	7.0	100 (15.8)	291	100 (0.140)	6
Fine sand	5.8	100 (62.6)	106	100 (0.008)	0
Silt clay	6.7	100 (2.6)	573	100 (0.213)	38
Silt loam	6.2	100 (3.4)	418	100 (0.090)	176

[a] Numbers in parentheses are mm water h^{-1}.
[b] Numbers in parentheses are g soil $m^{-2}\ s^{-1}$.

Source of nutrients to plants and animals: FGDs applied to soils provide not only Ca and S, but other mineral nutrients essential to plants (Mg, K, Zn, Cu, and B) especially when "stabilizing materials" (e.g. fly ashes, limestone, and alkalizing agents) are added. Of the nutrients added with "stabilizing materials", Mg is supplied when dolomitic limestone is used in the scrubbing process, while the other nutrients come primarily from fly ashes and other materials added to FGDs. Although plants do not require Se, many animals do [35]. Mineral nutrients acquired by plants are commonly transferred to animals. FGDs containing Se may provide plants sufficient Se so that animals consuming these plants would not need Se supplemented feeds. However, the narrow range between plant Se concentrations that are toxic to animals and that required by animals needs to be monitored when FGDs with high Se are used.

Improve soil physical properties: Important benefits of FGDs added to soil are improved physical properties.

Table 3
Change in water-extractable P from eight soils amended with different levels of FGD (modified from Stout et al. [50])

Soil	FGD added to soil (g kg^{-1} soil)			
	0 (%)	5 (%)	10 (%)	20 (%)
Paulding	100 (16.0)[a]	64	41	35
Harleton	100 (14.7)	66	53	41
Calvin	100 (13.2)	67	63	58
Berks	100 (12.1)	67	52	44
Pocomoke	100 (11.8)	48	42	36
Metapeak	100 (8.7)	74	70	64
Cove	100 (8.1)	49	44	40
Lauralwood	100 (1.7)	65	59	47

[a] Numbers in parentheses are water-extractable P in mg l^{-1}.

Soils with added FGDs have been reported to have less surface crusting and compaction, greater water infiltration and holding capacity, greater aggregate stability, and less water runoff and erosion (Table 2; [31,38]). Surface soil crusting is often prevented when rainfall events occur if FGDs have been applied. FGDs can provide electrolytes to overcome dispersion of soil particles. Calcium has great ability to enhance flocculation/aggregation of soil particles, particularly clay, and keep soils friable, enhance water penetration, and allow roots to penetrate hard/compact soil layers [38].

Amelioration of sodic soil problems: Gypsum has been applied for a long time on sodic soils to alleviate compaction (dispersion of soil particles) caused by elevated Na saturation and to improve water penetration [3,57]. Calcium readily replaces Na on soil/clay exchange sites to enhance soil flocculation and stability [38]. However, some materials used to capture SO_2 contain sufficient Na that end-products could enhance Na dispersion of clay particles and reduce soil water infiltration. Caution is needed when using high-Na FGDs on land. Information about gypsum use on land is applicable, and has been extensively reviewed [2,3,31,44,47,52,53].

Reduce phosphorus availability/transport: Another benefit of FGD use on land can be to reduce solubility of P in high-P soils or when high-P materials (poultry and animal manures and composts) have been applied. Some major cropping areas of USA contain higher levels of P than recommended by soil test for agricultural crop production [48]. High levels of P in surface soil may lead to P export and eutrophication of streams, lakes, and ground water. For example, outbreaks of the toxic dinaflagellate alga *Pfiesteria piscidia* in eastern USA waterways have been attributed to high levels of P in surface runoff water [50]. FGDs with high $CaSO_4$ can reduce solubility of P in soil by converting readily exchangeable P to less soluble P compounds, which may reduce P loss from water run-off and transport into surface and ground waters (Table 3; [25,26]).

Miscellaneous benefits: Solid feedlot/containment pads to keep animals from wading/wallowing in mud/mire during wet seasons [11,32] and solid pads for storage and preservation of dried hay for feeding animals [11] have been built from FGDs containing sufficient "stabilizing materials". Impermeable liners for ponds have also been constructed using FGD materials [11,58]. Another beneficial use of FGDs has been in co-utilization (production of new products from combination of two or more other products) with organic materials (animal manure, biosolids, yard waste, municipal waste) to form amendment mixtures [10,43]. FGDs can provide essential plant nutrients (e.g. Ca, S, K, and B), and organic materials can provide needed N and P. Co-utilization products are often used as potting mixes and manufactured soils. Organic matter is important for maintaining or improving soil structure/friability and water holding capacity. FGDs with high alkalinity have also been used as disinfecting agents in stabilization of organic materials [33].

3. Constraints

Soil pH: FGD gypsum or relatively pure mineral gypsum, even at high levels, does not normally increase pH of acidic soil very much (Table 1). Soil pH increases primarily from

Table 4
Soluble salts (electrical conductivity (EC), 1 soil:1 water)) in acidic soil amended with different levels of various FGDs and CCPs (from Clark et al. [16])

CCP in soil (%)	Fly ash		FBC		Stabilized FGD		FGD gypsum		
	Class F (dS m^{-1})	Class C (dS m^{-1})	FBC-1 (dS m^{-1})	FBC-2 (dS m^{-1})	FGD-1 (dS m^{-1})	FGD-2 (dS m^{-1})	FGD in soil (%)	FGD-A (dS m^{-1})	FGD-B (dS m^{-1})
0	0.17	0.12	0.09	0.12	0.17	0.09	0	0.11	0.11
0.5		0.15	0.45	0.62		0.63	5	1.48	1.22
1	0.35	0.19	0.98	1.34	1.06	1.13	10	1.67	1.09
2	0.31	0.35	1.75	1.87	1.15	1.53	25	1.62	1.14
3	0.34	0.56	1.65	2.00	1.48	1.78	50	1.71	1.22
5	0.56	0.97	1.83	2.09	1.54	2.08	75	1.68	1.20
10	0.94	1.54		1.12	2.31				
20				2.50					
25		6.47							
FGD/CCP EC	2.96	1.78	3.96	6.68	2.13	2.69		1.80	1.67

Table 5
Degree of Mg deficiency on leaves of maize grown in acidic soil amended with different Ca/Mg ratios as $CaCO_3$ and FGD (from Clark et al. [19])

Treatment	FGD in soil (g kg^{-1})	Ca/Mg ratio					
		0/0	1/0	1/0.01	1/0.05	1/0.1	1/0.5
Unamended soil		+ [a]					
$CaCO_3$	2.5		+++	+++	0	0	0
	5.0		+++	0	0	0	0
FGD-A	2.5		+++	+++	0	0	0
	5.0		+++	+	0	0	0
FGD-B	2.5		+++	+++	0	0	0
	5.0		+++	+	0	0	0

[a] (+++), Severe Mg deficiency symptoms; (+), Slight Mg deficiency symptoms; (0), no Mg deficiency symptoms.

alkalinizing agents like $CaCO_3$, CaO, and $Ca(OH)_2$ that are added to stabilize the FGD products. For example, acidic soil with an initial pH 4.0 had pH values of 4.1, 4.2, 4.3, 4.6, and 5.5 when FGD gypsum was added at 5, 10. 25, 50, and 75% (112, 224, 560, 1120, and 1680 ton ha^{-1}, respectively) to soil mixes (Table 1). FGD gypsum used in these studies had low $CaCO_3$ equivalencies (~6%), so these products had little effect on soil pH. Certain stabilized FGDs and fluidized bed combustion (FBC) and CaO products increased soil pH of an acidic soil to undesirably high values when added at rates >5% (Table 1; [16]). Materials like CaO and $Ca(OH)_2$ can increase soil pH excessively because of high reactivity. Raising soil pH to >8 is generally detrimental to plant growth. Optimal pH for growth of plants in acidic soil is related more to reduced availability of toxic elements and availability of essential nutrients than to H-ion concentration.

Excess soluble salts: Many detrimental effects of high soil pH on plants are caused by excessive soluble salts (e.g. B, K, Mg, Na, and Cl). High salts in FGDs normally come from added "stabilizing materials" rather than from the relatively insoluble $CaSO_4$. Sensitive and moderately sensitive plants to salt normally tolerate salt levels at electrical conductivity (EC) values between 1.5 and 3.5 dS m^{-1}, respectively, before detrimental effects occur [34]. The EC values in acidic soil receiving various rates of several FGDs were not above 3.5 dS m^{-1}, except for very high levels of a FBC product (Table 4; [16]). Detrimental salt effects would not normally be expected from most FGDs unless added at high rates.

Calcium imbalances with other nutrients: FGDs contain high Ca which may potentially cause imbalances of other mineral nutrients such as Mg, K, and P [30]. Magnesium deficiency was common when maize was grown in acidic soil with various FGDs [15,19,51]. Once Mg was added to provide soil Ca/Mg ratios of ~30:1, Mg deficiency symptoms were alleviated (Table 5). Differences among various sources of Mg for effectiveness in enhancing plant growth were also noted [61]. The FGD product which enhanced maize growth the most at low rates was one with enriched Mg [16,18]. Acidic soil amended with FGD plus K also benefited plant growth [51]. High Ca (or high soil pH) may also reduce solubility of P [25,26,50], Fe [14,35], and Zn [35]. If sufficient Ca is added to form Ca–P precipitates or if pH becomes sufficiently high to inactivate P, P deficiencies in plants may occur. In addition, high soil pH normally converts Fe^{2+} (readily available to plants) to Fe^{3+} (low availability to plants).

Aluminum toxicity: Calcium readily exchanges with active Al on exchange sites of soil particles [23]. Since Al becomes more available and potentially more toxic to root growth at low soil pH [28], low levels of Ca from FGDs may increase soil solution Al and enhance Al toxicity in soil where pH has not risen sufficiently (Table 6; [7,24]). However, toxic forms of Al may be inactivated by high Ca and S levels [23]. When less than 5% $CaSO_4$ was added to acidic soil, maize growth was inhibited, but once $CaSO_4$ had been added at higher rates, growth inhibitions were alleviated (Table 6). The pH of soil with $CaSO_4$ added up to 5% was no more than ~0.2 units higher than the

Table 6
Dry matter (DM) of maize grown in acidic soil amended with different levels of $CaSO_4$ (from Clark et al. [17])

$CaSO_4$ in soil(%)	Shoot DM (mg $plant^{-1}$)	Root DM (mg $plant^{-1}$)	$CaSO_4$ in soil (%)	Total DM (mg $plant^{-1}$)
0	208	258	0	367
0.25	142	142	5	392
0.5	103	86	10	516
1.0	120	96	25	580
2.0	171	143	50	409
4.0	202	172	75	359

Table 7
Whole plant dry matter (DM) of maize grown in acidic soil amended with different levels of $CaSO_3$ (from Clark et al. [17])

$CaSO_3$ in soil (%)	Plant DM (mg plant^{-1})
0	466
0.25	307
0.5	231
1.0	223
2.0	136
4.0	51

original soil pH of 4.0 (Table 1). Thus, Al toxicity occurred at this level of $CaSO_4$ before being ameliorated by higher levels of $CaSO_4$ (Table 6).

Sulfite toxicity: FGD scrubber sludges often contain high levels of sulfite. Sulfite applied to acidic soil even at low levels can be toxic to plants (Table 7; [8]), so use of high sulfite FGDs may be detrimental to plants unless sulfite is oxidized. Sulfite oxidation to sulfate in soil occurs relatively rapidly (days or weeks) [9,45]. Sulfite from FGDs spread on land during the off-season or sufficiently early before planting will likely be oxidized before planting time. High soil pH and moisture can increase time needed for sulfite oxidation because of low oxygen available for reaction [9]. In soils with low pH, sulfite may also form SO_2, which is highly toxic to plants/insects [42]. When oxidized FGDs are used, they are essentially gypsum products, and information about gypsum use on land would be applicable [2,3,31,44,46,47,52,53].

Boron toxicity: Plant B toxicity is common when FGDs are applied to land, especially for FGDs with added fly ash or other "stabilizing materials" (Table 8; [12,51]). Even though B is essential to plants, the difference between sufficiency and toxicity is narrow [35]. Boron is also water soluble and readily leaches from soil. Once soil or FGD with high B has been leached, B toxicity may be alleviated. Boron toxicity is especially apparent in plants grown under controlled conditions where soil volumes and leaching are limiting, but is alleviated fairly rapidly when FGDs are applied in the field [41,60]. Level of B provided to animals is not regulated [1]. Plants grown in soil with high pH normally have lower leaf B concentrations than plants grown with low pH [12,15]. Plants grown with lower compared to higher soil pH also appear to tolerate higher leaf B concentrations before becoming toxic [15]. Since "stabilizing materials" added to FGDs are often sources of B to plants when added to soil, caution is needed not to add excess amounts. Plants like alfalfa need relatively high levels of B for optimal growth [12]. In studies where several FGD (and other CCP) products were used to grow maize, leaf B concentrations were near toxicity levels (150–200 mg kg^{-1}) for plants grown with some products (Table 8), especially at high levels, because many of the products originally contained fairly high B [16,20].

Excess accumulation of nutrients in plants: FGDs contain high Ca and S, so if these materials are added to soil at sufficiently high levels, both Ca and S could potentially accumulate at excessive concentrations in plant tissue. Calcium can especially interact with other mineral nutrients to induce deficiencies (discussed above). Maize grown in acidic soil with FGDs added at various levels did not acquire excessive leaf Ca (>10–15 g kg^{-1}) even though high Ca was available (Table 9). However, leaf S concentrations were near excess (>5.0 g kg^{-1}) when plants were grown with relatively moderate treatment levels (>3%) of these same FGDs (Table 9). Leaves did not contain excessive Ca or S when maize was grown in acidic soil amended with as high as 75% FGD gypsum. Other essential minerals to plant growth (and animals) could be affected by addition of high levels of FGD. Normally, Cu and Zn do not accumulate to excess concentrations in plants unless plants are grown in

Table 8
Whole plant dry matter (DM) and leaf B concentrations of maize grown in acidic soil amended with different levels of various FGDs (from Clark et al. [20])

FGD in soil %	Plant DM (mg plant^{-1})	Leaf B (mg kg^{-1})	Plant DM (mg plant^{-1})	Leaf B (mg kg^{-1})
Stabilized FGD				
	FGD-1		FGD-2	
0	449	38	606	28
0.5			942	49
1	543	57	948	53
2	631	120	1130	151
3	515	162	825	207
5	365	257	511	255
10	69	479		
FGD gypsum				
	FGD-A		FGD-B	
0	188	22	190	17
5	181	19	275	17
10	185	24	369	15
25	247	36	467	17
50	434	66	402	24
75	348	106	364	65

Table 9
Calcium and S concentrations in leaves of maize grown in acidic soil amended with different levels of FGDs (from Clark et al. [21])

FGD in soil	Calcium		Sulfur	
Stabilized FGD				
	FGD-1 (g kg^{-1})	FGD-2 (g kg^{-1})	FGD-1 (g kg^{-1})	FGD-2 (g kg^{-1})
0	1.15	1.26	1.54	1.80
0.5		6.27		4.75
1	6.72	7.84	4.50	3.98
2	7.45	7.35	4.17	2.43
3	8.63	8.14	3.17	2.54
5	9.20	10.39	2.96	2.85
10	9.08		5.46	
FGD gypsum				
	FGD-A	FGD-B	FGD-A	FGD-B
0	1.59	1.53	2.13	2.23
5	7.86	8.35	8.62	5.02
10	8.15	8.58	8.16	3.63
25	6.95	10.75	5.06	2.64
50	5.13	11.95	2.56	2.48
75	4.84	9.74	2.29	2.14

highly contaminated soils (e.g. smelter affected and industrially contaminated sites) [35]. Excess Mo in FGDs has the potential to induced Cu deficiency ("molybdosis") in ruminant animals [56].

Trace element toxicity: One of the major concerns for FGD use on agricultural land has been potential hazard of trace element (i.e. Ag, As, B, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn) contamination in water and plants. Of particular concern is when toxic concentrations of these elements enter the food/feed chain. The most serious potential trace element hazards are for B, As, Se, and Mo [29,30,59], although the other elements may pose concerns under some conditions. Boron, As, Se, Mo are anionic and usually have higher availability as soil pH increases compared to cationic elements (Cd, Cr, Cu, Ni, Pb, and Zn) that have decreased solubility as soil pH increases [3,39]. Boron, Mo, Cu, Ni, and Zn are essential to growth of many plants and Se is essential to animals, while As, Cd, Cr, and Pb are not essential to either plants or animals [35]. The major source of trace elements in FGD products comes from "stabilizing materials" added to FGDs. Because of these concerns, limits for trace elements have been established in leachates (TCLP), drinking water, and land loading (Table 10; [27]).

When concentrations of trace elements have been reported in soils amended with FGDs or in plants grown in soil amended with FGDs, they have usually been below established standards and are often below detectable limits [4,5,22,49]. For example, mean leaf concentrations of Ni, Pb, Cd, and Cr varied somewhat depending on type and level of FGD added to acidic soil (Table 11), and mean

Table 10
Summary of trace element concentrations in plant tissue and soils (mg kg^{-1}) and in leachates (mg l^{-1})

Conditions	Ni	Pb	Cd	Cr	Ref.
Mean for maize leaves (15 FGDs/ CCPs in soil at various levels)	1.22	1.28	0.31	0.62	[22]
Normal in plant foliage (range)	0.1–5	2–5	0.1–1	0.1–1	[13]
Mean in uncontaminated soil	25	50	0.5	50	[27]
Mean of five soil groups	22	29	0.53	54	[27]
Range	0.2–450	0.2–450	0.01–2.7	1–1100	[27]
TCLP leachate	–	5.0	1.0	5.0	[3]

Table 11
Mean leaf concentrations of Ni, Pb, Cd, and Cr of maize grown in acidic soil amended with different levels of FGDs (from Clark et al. [22])

Type of FGD		Ni (mg kg^{-1})	Pb (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})
Stabilized FGD	FGD-1	1.06	1.49	0.06	0.41
	FGD-2	1.50	1.65	0.54	0.44
FGD gypsum	FGD-A	0.80	0.92	0.24	0.62
	FGD-B	0.39	0.83	0.27	0.36

concentrations (mg kg^{-1}) over all levels and FGDs used were 1.22 for Ni, 1.28 for Pb, 0.31 for Cd, and 0.62 for Cr, which were below established standards and at concentrations considered normal for plant tissue (Table 10; [13]). Of interest was that leaf concentrations of Ni, Pb, and Cd were often higher for plants grown in unamended acidic soil than in FGD amended soil.

4. Conclusions

When used appropriately, FGDs should benefit agricultural land without causing contamination or detrimental effects. Several other constraints about use of FGDs on agricultural land may arise that are beyond the scope of this article. These include such items as regulations, economics and common barriers (e.g. high transportation costs, costs of conversion to acceptable products for hauling and application, high moisture, guaranteed quality, consumer acceptance, and market outlets), relatively low benefits received compared to amount needed for desired results, and lack of management information. Evidence continues to accumulate that FGD application to land could be viable/feasible and provide benefits to soils/plants.

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